Searching for chemical inhomogeneities in open clusters

Analysis of the CN and CH molecular band strengths in NGC 2158, NGC 2420, NGC 2682, NGC 7789, and Berkeley 29^{*}

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ABSTRACT

Context. The total mass of a cluster, which is the main parameter determining its ability to host more than one stellar generation, may constitute a threshold below which the cluster is able to form only a single stellar population.

Aims. Our goal is to investigate the existence of star-to-star variations in CN and CH band strengths, which are related to the N and C abundances, respectively, among the stars in five open clusters (NGC 2158, NGC 2420, NGC 2682, NGC 7789, and Berkeley 29). These variations are observed in globular cluster stars and they are linked with the existence of multiple populations. Since these systems are less massive than globular clusters, our results may allow us to constrain the lowest mass necessary to form more than one stellar population.

Methods. We measured the strength of the CN and CH bands, which correlate with the C and N abundances, using four molecular indices in low-resolution SDSS/SEGUE spectra.

Results. For four of the open clusters (NGC 2158, NGC 2420, NGC 2682, and Berkeley 29) we found that all the stars studied in each of them have similar CN and CH band strengths within the uncertainties, since neither anomalous spreads nor bimodalities have been detected in their CN and CH distributions. In contrast, we found an anomalous spread in the strength of the CN molecular band at 3839 Å for NGC 7789, which is larger than the uncertainties. However, the small number of stars studied in this cluster implies that further analysis is needed to confirm the existence of chemical inhomogeneities in this cluster.

Key words. Galaxy: disk – open clusters and associations: general – stars: abundances

1. Introduction

It seems that almost all properly studied Galactic globular clusters (GCs) host multiple stellar populations that explain the previously known star-to-star variations in the chemical abundances of light elements such as C, N, Na, O, Al and Mg (e.g. Gratton et al. 2012, and references therein). Similar features have been reported in extragalactic GCs (e.g. Letarte et al. 2006; Mucciarelli et al. 2009). Several main-sequence (MS) turn-offs or anomalous spreads in this region have been observed in intermediate-age and young massive clusters in the Magellanic Clouds (e.g. Glatt et al. 2008; Milone et al. 2009). Although several hypotheses have been proposed to explain these findings, the most widely accepted one is the so-called self-enrichment scenario first presented by Da Costa & Cottrell (1980). According to this hypothesis, a stellar cluster has experienced two or more star formation episodes, or extended periods of star formation. Therefore, the subsequent stellar populations born from the interstellar medium have been polluted by material ejected from previous generations. This material may have been synthesized through the CNO cycle, so that the younger populations have become enhanced in He, N, Na and Al and depleted in C, O, Ne, and Mg. Although the main progenitors of this polluted material are still unclear, the most accepted candidates

are either intermediate-age asymptotic giant branch (AGB) stars (e.g. D’Antona & Ventura 2007) or fast-rotating massive stars (e.g. Decressin et al. 2007).

The ability of a stellar cluster to retain the polluted material from which the subsequent stellar populations are formed may depend mainly on the gravitational potential of the cluster. Other variables such as age, metallicity, or environment may also play a role in this context. Therefore, a minimum mass may be required to retain the material ejected by the first generations. From an observational point of view, this limit may lie between 10^4 and $10^5 M_{\odot}$ (e.g. Mucciarelli et al. 2009; Carretta et al. 2010). However, these values refer to present-day mass and may have been higher at the moment of the cluster’s formation since it is expected that clusters have lost a significant fraction of their initial mass, in the form of either gas or stars during their lifetime (Baumgardt et al. 2008; Lamers et al. 2010). Theoretical investigations point to an initial mass limit between $\sim 10^5$ and $10^6 M_{\odot}$ (e.g. Vesperini et al. 2010; Bekki 2011).

Only a handful of GCs are known with masses lower than $10^5 M_{\odot}$. Two systems in this mass range, Palomar 12 and Terzan 7, seem not to have star-to-star variations in light element abundances, although only five stars have been studied in the best case (Cohen 2004; Tautvaišienė et al. 2004; Sbordone et al. 2005, 2007). Similar results have been found by Kayser et al. (2008) from the analysis of CN and CH molecular bands, which are related to N and C abundances, respectively,

^{*} Full Table 2 and Tables 4, 6–8 are available in electronic form at <http://www.aanda.org>

Table 1. Information about studied clusters.

Cluster	α_{2000} hrs	δ_{2000} deg	Age Gyr	$\langle v_r \rangle$ km s ⁻¹	[Fe/H] dex	Radius arcmin	Stars ^a	Ref.
NGC 2158	06:07:25	+24:05:48	1.0	24.9 ± 1.9	-0.15 ± 0.14	8.0	35	1, 3, 4
NGC 2420	07:38:23	+21:34:24	2.0	69 ± 5	-0.39 ± 0.20	12.0	67	1, 3, 5
NGC 2682	08:51:18	+11:48:00	2.6	36 ± 6	0.01 ± 0.07	21.0	46	1, 3, 6, 7
NGC 7789	23:57:24	+56:42:30	1.4	-58 ± 6	-0.04 ± 0.05	28.84	11	1, 3, 6, 7, 8
Berkeley 29	06:53:18	+16:55:00	1.1	24.7 ± 0.4	-0.42 ± 0.07	7.5	9	1, 2, 3

Notes. ^(a) This is the total number of stars used in our analysis for each cluster as a function of their spatial distribution, radial velocities, metallicities and position in the colour–magnitude diagram and with photometric magnitudes and a good available signal-to-noise ratio spectrum (see text for details).

References. (1) Dias et al. (2002); (2) Sestito et al. (2008); (3) Carrera & Pancino (2011); (4) Jacobson et al. (2011); (5) Chen et al. (2004); (6) Carrera et al. (2007); (7) Friel et al. (2002); (8) Wu et al. (2007).

in low-resolution spectra. However, Pancino et al. (2010b) analysed similar data in 23 stars of Palomar 12, finding a clear bimodal distribution of the CN band strengths and anti-correlation with the CH band strengths. Star-to-star variations in Na and O abundances have been detected recently by Geisler et al. (2012) in a sample of 21 giant stars in the old (~ 8 Gyr, Brogaard et al. 2012) and metal-rich ([Fe/H] $\sim +0.40$) open cluster (OC) NGC 6791 with a present-day mass similar to that of Palomar 12 and Terzan 7 ($10^4 M_\odot$, Platais et al. 2011). Carrera (2012b, hereafter Paper I) found that the star-to-star variations in the strengths of the CN and CH molecular bands are observed not only in red giant branch (RGB) objects but also among MS stars. Moreover, NGC 6791 shows unexpectedly wide RGB and MS, which could be related to the existence of an age spread of about 1 Gyr (Twarog et al. 2011). However, they could also be explained in terms of the existence of differential line-of-sight reddening (Platais et al. 2011). In contrast, chemical variations in light element abundances have not been observed in a sample of 30 stars in the OC Berkeley 39 (Bragaglia et al. 2012). This cluster has a similar mass and age to that of NGC 6791, although it is more metal-poor ([Fe/H] ~ -0.21). Other investigations on OCs have also investigated the existence of star-to-star variations in light element abundances from high-resolution spectroscopy without success, although the number of stars analysed in each cluster is small (e.g. de Silva et al. 2009; Smiljanic et al. 2009; Pancino et al. 2010a; Carrera & Pancino 2011). The strengths of CN and CH molecular bands in low-resolution spectra have also been studied in several OCs with the same results, although only about ten stars were studied in the best of the cases (e.g. Smith & Norris 1984; Norris & Smith 1985; Martell & Smith 2009). Extended MS turn-offs have also been found in two clusters, SL 529 and SL 862, in the Large Magellanic Cloud (LMC) with masses similar to that of NGC 6791, although they are younger (Milone et al. 2009; Piatti 2013). These features have also been interpreted in terms of the existence of an extended period of star formation in both clusters. However, chemical analyses are needed to confirm, or discard, the existence of the star-to-star abundance variations in the two clusters.

It is essential to better constrain the minimum cluster mass required to form multiple stellar populations. For this purpose, it is necessary to properly sample less massive systems by analysing a statistically significant number of stars. Following the same procedure as used in Paper I, the goal of this paper is to analyse the strengths of the CN and CH molecular bands in stars at different evolutionary stages in five OCs: NGC 2158, NGC 2420, NGC 2682 (M 67), NGC 7789, and Berkeley 29. The last two have present-day masses similar to that of NGC 6791.

Although this technique does not supply chemical abundances directly, it does provide valuable information about the existence of star-to-star variations in C and N abundances. The observational material utilized in this paper is presented in Sect. 2. The molecular indices used to determine the CN and CH band strengths are presented in Sect. 3 with the procedure used to obtain their distributions. The results obtained for each cluster are discussed in Sect. 4. Finally, the main results are discussed and summarised in Sects. 5 and 6, respectively.

2. Observational material

In the framework of the Sloan Extension for Galactic and Understanding and Exploration (SEGUE) survey (Yanny et al. 2009), low-resolution ($R \sim 2000$) spectra were obtained for $\sim 240\,000$ stars over a wavelength range of 3800–9200 Å. These include several globular and open clusters, including those studied here, which were used to validate the SEGUE Stellar Parameter Pipeline (SSPP, Allende Prieto et al. 2008; Lee et al. 2008a,b). The reduced spectra with atmosphere parameters (T_{eff} , $\log g$, [Fe/H]), radial velocities, etc., derived for observed stars were made public in the eighth Sloan Digital Sky Survey (SDSS) data release (Aihara et al. 2011). Two examples of the spectra analysed in this paper are shown in Fig. 1. The procedure for obtaining this information can be summarised as follows. Raw spectra are first reduced by the SDSS spectroscopic reduction pipeline, as described in detail by Stoughton et al. (2002), which provides flux- and wavelength-calibrated spectra with initial determinations of the radial velocities and spectral types. More accurate radial velocities are calculated in a subsequent step by SSPP, together with determinations of metallicity, effective temperature, and surface gravity.

The same method used in Paper I and fully described by Smolinski et al. (2011) was used to constrain the members of each cluster. In brief, we first rejected those stars located farther than a given distance from the cluster centre (left panels of Fig. 2). The cluster centres and radius used in each case are listed Table 1. In general, this distance has been chosen as half of the tidal radius of each cluster. Exceptional cases were NGC 2158 and NGC 7789 for which we used the tidal radius, since it seems that there are still cluster stars in both cases beyond the assumed tidal radius. In the following step, we used the values provided by SSPP to discard those stars with radial velocities and [Fe/H] that were not within 3σ of the mean radial velocity and [Fe/H] that was assumed for each cluster and listed in Table 1 (right panels of Fig. 2). The total number of stars considered as cluster members from these criteria were 63, 115, 91,

Fig. 1. Example of two spectra over-plotted, one in grey (3569) and one in black (4751), for two stars in NGC 7789 with different CN band strengths. The *top panel* shows the wavelength region which includes the CN band at 4142 Å and the CH band at 4300 Å. The wavelength region which contains the CN band at 3839 Å has been plotted in the *bottom panel*. The windows used to determine the strength of each molecular band have been marked with horizontal arrows, whereas vertical dashed lines show the edges of these windows.

29, and 31 for NGC 2158, NGC 2420, NGC 2682, NGC 7789, and Berkeley 29, respectively.

Although SDSS data releases also provide information about the magnitudes of the target stars, we preferred to use other sources, since the SDSS photometric package is not able to properly handle high-density crowded fields typical of the central areas of clusters, as denoted by [An et al. \(2008\)](#). For NGC 2420 and NGC 2682 we used the photometry obtained by [An et al. \(2008\)](#) in Sloan *ugri* bandpasses. For the other three systems (NGC 2158, NGC 7789, and Berkeley 29), we used the photometry obtained by [Carraro et al. \(2002\)](#), [Gim et al. \(1998\)](#) and [Tosi et al. \(2004\)](#), respectively. Unfortunately, we have not been able to match all the stars selected as cluster members from the criteria described above with the photometric sources. The total number of stars that meet with these criteria and that also have available photometric magnitudes are 47, 114, 74, 25, and 20 for NGC 2158, NGC 2420, NGC 2682, NGC 7789, and Berkeley 29, respectively. Finally, these stars are grouped as a function of their position in the colour–magnitude diagrams. Selected stars have been over-plotted to the colour–magnitude diagram of each clusters with different symbols as a function of their evolutionary stage in Fig. 3: filled circles, crosses, and open stars for MS, RGB, and red clump (RC) stars, respectively. Stars discarded owing to their position in the colour–magnitude diagram or because their spectra have low signal-to-noise ratios have been plotted with open circles. Since not enough RGB stars have been observed in the clusters of our sample, we restricted our analysis to the MS stars with the exception of NGC 7789, in which the RC objects have been studied. The total number of stars used in each cluster are listed in Col. 8 of Table 1.

Fig. 2. *Left:* spatial distribution of all stars observed by SEGUE (dots) and those with available photometry (light grey) for each cluster. Dashed lines denote the radii used to select cluster members, which are marked as black circles. *Right:* radial velocity histograms of all stars observed by SEGUE (grey) and those located within the radii used to select cluster members (black). Dashed lines denote the radial velocity limits used (see Table 1). [Fe/H] distributions of stars selected for their radial velocity and [Fe/H] have been plotted in the *inset panels* with grey and black lines, respectively.

3. CN and CH band strengths

The strengths of the CN molecular bands at 3839 and 4142 Å and the CH band at ~4300 Å were determined using the same indices as defined in Paper I. We refer the reader to this paper and references therein for a detailed discussion about each index. In brief, we used a two index definition for the CN band at 3839 Å by [Norris et al. \(1981\)](#) and [Harbeck et al. \(2003\)](#). Each is optimized to sample RGB and MS stars, respectively. For the other two molecular bands, the CN and CH centred at 4142 Å and 4300 Å, respectively, we used the index definitions by [Norris & Freeman \(1979\)](#) and [Lee \(1999\)](#), respectively. As in Paper I, the uncertainty in each index was calculated by assuming pure photon (Poisson) noise statistics in the flux measurements as in [Pancino et al. \(2010b\)](#). The indices and errors determined with photometric magnitudes for each selected star are listed in Table 2. The median uncertainties for each cluster and index are listed in Table 3.

Two or more instrumental configurations were employed to observe three of our clusters: NGC 2420, NGC 2682, and Berkeley 29. Therefore, 102 stars in their regions were observed twice. Although none of them are within those selected as cluster members, they are very useful for checking the homogeneity of our data and providing an additional estimation of the uncertainties. To do this, each index was measured separately in the two spectra for each star. On average, the differences between the values obtained for each index for all the stars are: $\Delta(S_{3839N}) = 0.000 \pm 0.005$, $\Delta(S_{3839H}) = 0.000 \pm 0.005$, $\Delta(S_{4142}) = 0.003 \pm 0.003$, and $\Delta(CH_{4300}) = 0.000 \pm 0.003$. These differences are negligible, thus ensuring the homogeneity of the index determination used in this paper.

Table 2. Index measurements for the sample stars (excerpt).

Cluster	Plate ^a	Fiber ^a	RA	Dec	<i>g</i>	<i>V</i>	ID _{phot} ^b	<i>S</i> 3839 _H	<i>S</i> 3839 _N	<i>S</i> 4142	<i>CH</i> 4300
NGC 2158	2912	409	6:07:10.96	+24:09:33.5	17.51		899	-0.50 ± 0.03	-0.28 ± 0.03	-0.32 ± 0.03	-0.48 ± 0.03
NGC 2158	2912	416	6:07:14.18	+24:08:08.8	17.53		919	-0.49 ± 0.03	-0.28 ± 0.03	-0.33 ± 0.03	-0.48 ± 0.03
NGC 2158	2912	417	6:07:14.25	+24:10:13.0	17.85		1143	-0.49 ± 0.04	-0.26 ± 0.04	-0.32 ± 0.04	-0.47 ± 0.04

Notes. ^(a) Plate and fiber uniquely identify the spectrum used in the analysis for each star in the SDSS III database. ^(b) ID_{phot} identifies the star in the photometry used.

Table 3. Median uncertainties for each cluster and index and the σ of the Gaussian fit to the generalized histogram of each pseudo-index.

Cluster	<i>S</i> 3839 _H		<i>S</i> 3839 _N		<i>S</i> 4142		<i>CH</i> 4300	
	$\langle\sigma\rangle$	σ_{Gaussian}	$\langle\sigma\rangle$	σ_{Gaussian}	$\langle\sigma\rangle$	σ_{Gaussian}	$\langle\sigma\rangle$	σ_{Gaussian}
NGC 2158	0.025 ± 0.006	0.033 ± 0.001	0.027 ± 0.006	0.033 ± 0.001	0.026 ± 0.006	0.029 ± 0.001	0.025 ± 0.006	0.029 ± 0.001
NGC 2420	0.030 ± 0.008	0.034 ± 0.002	0.031 ± 0.009	0.035 ± 0.002	0.030 ± 0.008	0.031 ± 0.001	0.030 ± 0.008	0.031 ± 0.001
NGC 2682	0.034 ± 0.003	0.041 ± 0.000	0.036 ± 0.003	0.042 ± 0.000	0.033 ± 0.002	0.034 ± 0.000	0.033 ± 0.005	0.034 ± 0.000
NGC 7789	0.056 ± 0.002	0.079 ± 0.004	0.061 ± 0.002	0.089 ± 0.004	0.050 ± 0.001	0.058 ± 0.003	0.048 ± 0.001	0.049 ± 0.002
Berkeley 29	0.09 ± 0.02	0.12 ± 0.02	0.09 ± 0.02	0.12 ± 0.02	0.09 ± 0.02	0.10 ± 0.01	0.09 ± 0.02	0.10 ± 0.01

Fig. 3. Colour-magnitude diagrams of the five clusters in our sample with the location of our target stars: MS (filled circles); RGB (crosses), RC (stars), and discarded stars either from their position in the colour-magnitude diagram or by low signal-to-noise ratio spectra (open circles). The best photometries available in the literature have been used, although this implies different filter combinations since similar quality photometry for all the clusters in our sample is not available in the same bandpasses.

The strength of each molecular band depends not only on chemical abundance but also on the temperature and surface gravity of the star. Different approaches can be found in the literature to removing this dependence, such as fitting the lower envelope or the median ridge line of a given molecular index as a function of colour or magnitude. In our case, we performed a polynomial least-squares fit on half of the selected stars (randomly selected) in each cluster. For NGC 2158, NGC 7789, and Berkeley 29 we used a linear polynomial, while a quadratic

Fig. 4. Left: run of the strength of the molecular indices of MS stars in NGC 2158 vs. their *V* magnitudes. A line has been fitted (dashed line) to remove the temperature and gravity dependence and to obtain the corrected pseudo-indices. Right: normal (histogram) and generalized (solid line) distributions of each corrected pseudo-index. Dashed lines are the best single Gaussians fitted to each generalized distribution. Note that the dashed lines fall so closely to the solid lines in all the cases that it is difficult to distinguish them. The residuals between the single Gaussian and the generalized distribution are shown in the inset panels.

was used in the case of NGC 2420 and NGC 2682, where the selected stars cover a wide magnitude of ranges. This procedure was repeated 10^3 times using different random subsets each time. The final terms for each index were obtained as the median of the values obtained in each individual test. With this procedure, we tried to minimize the uncertainties due to the low number of object studied and the influence of the points on the edges.

Fig. 5. As in Fig. 4 but for NGC 2420.

Fig. 6. As in Fig. 4 but for NGC 2682.

The final fits adopted in each case are shown as dashed lines in left panels of Figs. 4–8 and are listed in Table 4. Finally, we calculated the corrected pseudo-indices, denoted by a δ that precedes the corresponding index, as the difference between the index and the adopted fit in each case. Histograms were obtained for each corrected index (right panels of Figs. 4–8). In each case, generalized histograms (solid lines) were derived by assuming that each star is represented by a Gaussian probability function centred on its index value, whose σ is equal to the uncertainty in the determination of the index. The obtained histograms are discussed in depth in the following section.

4. Cluster-by-cluster discussion

4.1. NGC 2158

Because of its apparent spheroidal shape, NGC 2158 was considered as a GC in the past. However, it is an intermediate-age OC (~ 2 Gyr, Carraro et al. 2002) with a slightly sub-solar metallicity (-0.28 , Jacobson et al. 2011) located towards the Galactic anti-centre at a Galactocentric distance $R_{gc} \sim 13.5$ kpc. Studies of this cluster have been hampered by the foreground contamination due to its low location in the Galactic plane.

To our knowledge, only two studies have obtained chemical abundances for NGC 2158 stars based on high-resolution spectroscopic analysis (see Carrera & Pancino 2011). These two works obtained different iron abundances. Jacobson et al. (2009) obtained $[\text{Fe}/\text{H}] = -0.03 \pm 0.14$, whereas Jacobson et al. (2011) derived $[\text{Fe}/\text{H}] = -0.28 \pm 0.05$. The latter suggests that this difference may be a consequence of the first value having been obtained from only one star and by different temperature scales. Unfortunately, none of these studies provided enough data to investigate the existence of the light element anti-correlations among the NGC 2158 stars.

In total, we have measured the CN and CH molecular band strengths for 35 MS stars in this cluster (Fig. 4). In general,

Fig. 7. As in Fig. 4 but for RC stars in NGC 7789. In this case the run of each index has been plotted as a function of $V - I$ colours.

a large scatter is observed in the V -index planes (left panels). This scatter can be explained by a large differential reddening in the NGC 2158 area, as is clearly observed in its colour-magnitude diagram (Fig. 3). However, the single Gaussians fitted to the generalized histograms of each index (dashed lines in right panels) have sigmas similar to the average uncertainty in each case (~ 0.03 ; see Table 3). There are no signs of bimodalities or anomalous spreads. The band strengths obtained in our analy-

Fig. 8. As in Fig. 4 but for Berkeley 29.

sis are well reproduced by a single Gaussian distribution, as it is denoted by the residuals between the generalized histograms (solid lines) and the fitted single Gaussians (dashed lines) plotted in inset boxes of the right panels. As in this paper, [Martell & Smith \(2009\)](#) analysed the strength of the CN molecular bands for six stars in the upper RGB and RC regions. Although their sample is small in comparison to ours, they found no evidence of star-to-star variations among the NGC 2158 stars, as in our case.

4.2. NGC 2420

NGC 2420 is a ~ 3 Gyr old intermediate-age OC with a distance modulus of $(m - M)_V = 11.9 \pm 0.3$ located beyond the solar circle at a Galactocentric distance of ~ 11 Kpc and 0.8 Kpc above the Galactic plane (e.g. [Pancino et al. 2010a](#)). It has traditionally been considered among the most metal-poor OCs with $[\text{Fe}/\text{H}] = -0.57 \pm 0.08$ (e.g. [Smith & Suntzeff 1987](#)). This has led to NGC 2420 being considered as a transition system between a solar-metallicity OC and metal-poor GC. However, more recent analysis based on high-resolution spectra pointed to an iron content slightly above solar. For example, [Pancino et al. \(2010a\)](#) obtained $[\text{Fe}/\text{H}] = -0.05 \pm 0.03$ from the analysis of three RC stars, whereas [Jacobson et al. \(2011\)](#) found $[\text{Fe}/\text{H}] = -0.20 \pm 0.06$ from the study of nine giants. Although [Pancino et al. \(2010a\)](#) derived abundances for Al, Mg, Na, and O, the small number of stars studied does not allow a proper investigation of the existence of (anti-)correlations between the abundances of these elements.

Although 114 MS stars were selected as members of NGC 2420 according to the criteria described in Sect. 2, we have discarded 67 of these because of their low signal-to-noise ratio. We have therefore determined the CN and CH band strengths for 47 MS objects. The run of each of them as a function of g magnitude is shown in the left panels of Fig. 5. Except for the S4142 index, it is observed that the strength of the molecular

indices decreases towards brighter magnitudes. The same trends are also observed in NGC 2158 (although probably blurred by the differential reddening in the line of sight), NGC 2682 and Berkeley 29. Similar trends were also found in Paper I for NGC 6791. This is explained because the temperature increases as the magnitude decreases for MS stars. The indices therefore decrease, since the formation of CN and CH molecules is more efficient at lower temperatures. In contrast, the S4142 CN index shows an opposite trend: the strength of this molecular band increases as magnitude decreases. We believe that this trend is artificial, since the variation is lower than the average uncertainty in the strength determinations, which is about ~ 0.03 (error bars in the left panels of Fig. 5) for the four indices analysed.

The distributions of the pseudo-indices for NGC 2420 are plotted in the right panels of Fig. 5. Again, there are no signs of bimodalities or dispersions larger than those expected from the uncertainties. The sigma of the Gaussian fits (dashed lines in the right panels of Fig. 5) is ~ 0.03 , which is very similar to the average uncertainty of each index (see Table 3). We note that the solid lines almost completely cover the dashed lines for all the indices studied (right panels of Fig. 5). From the residuals shown in the inset panels, it seems however that the generalized histograms are not exactly Gaussian. In any case, the symmetrical behaviour of these residuals only implies that the generalized histograms have a higher peak and wider wings than a Gaussian, but there is no evidence of the existence of multiple statistical populations. [McClure et al. \(1974\)](#) analysed DDO photometry in the C(41–42) bandpass, which includes the CN molecular band at 4142 Å for 12 giant stars in NGC 2420. As in our case, they found that all the studied stars have similar C(41–42) magnitudes and therefore, similar CN band strengths.

4.3. NGC 2682 (M 67)

NGC 2682 is a ~ 4.5 Gyr old and solar metallicity cluster with $[\text{Fe}/\text{H}] = +0.05 \pm 0.03$ (see [Pancino et al. 2010a](#), and references therein). It is one of the most well-studied OCs due to its low reddening, $E(B - V) = 0.04 \pm 0.02$, and proximity, $(m - M)_V = 9.67 \pm 0.11$. Chemical abundances from high-resolution spectroscopy have been derived by several studies using different spectral-type stars in NGC 2682 (see [Carrera & Pancino 2011](#), for a recent compilation). All of them agree on a similar iron content to that of the Sun. Many of these studies have also derived abundances of light elements such as C, N, Al, Mg, Na, and O. There is a wide spread among the values obtained by different authors for Mg and Na, which may be explained by the difficulties in measuring these elements, as pointed out by [Pancino et al. \(2010a\)](#). As in the case of NGC 2420, these authors derived Al, Mg, Na, and O abundances, but the small number of stars analysed prevented them from obtaining conclusions about the existence of (anti-)correlations among them.

In this case, we have determined the band strengths of 46 MS stars that show well defined sequences in the g -index planes (left panels of Fig. 6). The median uncertainties in the determination of the strengths of each index are between 0.03 and 0.04 (Table 3). In contrast with the other clusters in our sample, the strengths of the four indices studied increase towards fainter magnitudes, and therefore towards lower temperatures, as expected theoretically and observed in GCs (e.g. [Pancino et al. 2010b](#)) and in NGC 6791 (Paper I). The generalized distributions obtained for each pseudo-index (right panels) are very well reproduced by Gaussians, as the very small residuals plotted in the inset panels denote. In the right panels of Fig. 6 we note

that solid and dashed lines overlap. With dispersions similar to the median uncertainties for each index this implies that all the stars analysed in NGC 2682 have very similar CN and CH band strengths, and therefore, C and N abundances. The sigmas of the Gaussians fitted to each generalized histogram are listed in Table 3. As in the case of NGC 2420, our results are in good agreement with the conclusions obtained from DDO photometry in 36 red giant stars studied by [Janes & Smith \(1984\)](#).

4.4. NGC 7789

NGC 7789 is a ~ 1.5 Gyr old OC located at a Galactocentric distance of $R_{gc} \sim 9.4$ kpc and is about 0.2 kpc below the Galactic disc plane, which explains the relatively high reddening in its line of sight, $E(B - V) = 0.27 \pm 0.04$ (see [Pancino et al. 2010a](#), and references therein). Although studies based on photometry and low resolution spectroscopy assign a sub-solar metallicity to this cluster at $[Fe/H] \sim -0.24 \pm 0.09$ (e.g., [Friel et al. 2002](#)), high-resolution spectroscopic studies have found an iron content similar to that of the Sun: $[Fe/H] = +0.04 \pm 0.07$ ([Pancino et al. 2010a](#)). Although [Pancino et al. \(2010a\)](#) derived Al, Mg, Na, and O abundances in three RC stars, the small number of objects studied does not allow the existence of usual (anti)-correlations observed in GCs to be investigated.

In contrast with the other clusters in our sample, we have restricted our analysis of NGC 7789 to 11 RC stars, because no MS objects were observed in this cluster. Since RC objects are located almost at the same luminosity, it is not useful to use the magnitude to remove the temperature and gravity dependences. For this reason, we have plotted the run of the index strengths as a function of $V - I$ colour in the left panels of Fig. 7. Although the uncertainties in the four indices are relatively large (see Table 3), the expected increase in the band strengths towards redder colours, and therefore, towards lower temperatures is observed in all of them. The $CH4300$ index shows a unimodal distribution within the uncertainties, as has been observed in the other clusters studied here. However, the $S4142$ index shows a generalized histogram that although it is relatively well fitted by a single Gaussian has a sigma that is slightly larger than the average uncertainty. Hints of bimodalities are observed in the histograms of both $S3839_H$ and $S3839_N$ which is particular in the latter, defined to sample giant stars, such as on the RC. However, these bimodalities are smoothed when the generalized distributions are obtained by considering their uncertainties. However, none of them is well reproduced by a single Gaussian, as the residuals plotted in inset boxes of the right panels indicate. This broadening is not explained by the uncertainties, since the sigmas obtained from the single Gaussian fits are larger than the average error bars (see Table 3). We have also investigated the possibility that the observed scatter is independent of the V magnitude, i.e. if the stars analysed are in different evolutionary stages. The star with the lower $S3839_H$ index is the faintest one with $V = 13.4$. There are no other stars in our sample with similar magnitudes. Therefore, its lower CN band strengths could be explained by the fact that this star would be in a different evolutionary stage than the others. In contrast, we find that the objects with lower CN band strengths have almost the same magnitudes than others with higher values for the other stars analysed. We have also investigated to see if our result is influenced by the existence of binaries in our sample. According to the WEBDA database, only two stars in our sample are spectroscopic binaries. These stars, 8383 and 9831, fall in the most populated part of the $V - I$ vs. indices diagrams at around $V - I \sim 1.32$. The unexpected broadenings observed in the gen-

eralized histograms of $S3839_H$ and $S3839_N$ indices do not disappear if these stars are removed from the sample. Therefore, we conclude that our result is not explained by the existence of stars in different evolutionary stages or binaries in our sample. The spectra of two stars with similar $V - I$ colours but different $S3839_H$ and $S3839_N$ strengths are shown in Fig. 1. A similar behaviour was observed in NGC 6791 RC stars in Paper I. However, both the small number of stars sampled and the relatively low signal-to-noise ratio of the spectra used in our analysis prevent us from drawing more conclusions, which implies large uncertainties. Although we cannot confirm the existence of star-to-star variation in CN band strengths, we also cannot discard them. The DDO photometry were obtained by [Janes \(1977\)](#) for 22 giants in NGC 7789. From the analysis of the magnitudes obtained in the $C(41-42)$ bandpass, they did not find evidence of an intrinsic range of CN strengths in contradiction with the result obtained here. However, the lower sensitivity of the CN molecular band at 4142 Å compared to the one located at 3839 Å may explain this discrepancy.

4.5. Berkeley 29

Berkeley 29 is a very interesting cluster because of its location towards the Galactic anti-centre in the outskirts of the Galactic disc at a Galactocentric distance of $R_{gc} \sim 23$ Kpc and height of ~ 2 Kpc above the disc. Its intermediate-age, ~ 3.5 Gyr, and low metallicity, $[Fe/H] \sim -0.4$, (e.g. [Tosi et al. 2004](#); [Bragaglia et al. 2005](#)) match within the framework of Galactic evolution, despite the suggestion by [Frinchaboy et al. \(2004\)](#) that Berkeley 29 is associated with the Canis Major overdensity. Because Berkeley 29 is a very interesting object, we have included it in our sample despite the low number of stars selected as members in comparison to the other systems analysed with the exception of NGC 7789.

Of the 20 objects selected as Berkeley 29 members from the criteria described in Sect. 2, we have determined CN and CH band strengths for only nine MS stars. Their run as a function of V magnitudes are shown in the left panels of Fig. 8. The trends are similar to those observed in other clusters in our sample, although the scatter is larger because of the larger uncertainties motivated by the lower signal-to-noise ratios of the spectra acquired for Berkeley 29 stars. Moreover, the generalized histograms for each pseudo-index are well reproduced by single Gaussians with sigmas similar to the median uncertainties in each case (see Table 3). This implies that the generalized histograms are mainly modulated by the large uncertainties in the determinations of the four molecular indices analysed, which prevents us from obtaining any conclusion about the existence of star-to-star variations. Within the uncertainties, we therefore conclude that we find no evidence of the existence of significant differences in the strengths of the CN and CH molecular bands and in the abundances of the analysed stars.

5. Discussion

The existence of multiple populations has been reported in massive clusters with a wide range of ages from old GCs to intermediate-age and young populous systems in the Magellanic Clouds. They are clearly linked with the star-to-star variations in light element chemical abundances reported in almost all properly studied GCs in the Galaxy, in the LMC, and Fornax dwarf spheroidal galaxy. However, the same chemical inhomogeneities have not been observed in intermediate-age populous clusters of

Table 5. List of previously studied open clusters.

Cluster	Stars	Type	Ref.
NGC 188	13	MS	Norris & Smith (1985)
NGC 188	7	RC/RGB	Martell & Smith (2009)
NGC 2158	6	RC/RGB	Martell & Smith (2009)
NGC 2158	10	RC	Smith & Norris (1984)
NGC 6791 ^a	31	RC/RGB	Hufnagel et al. (1995)
NGC 6791	97	MS/RGB/RC	Paper I
NGC 7789	10	RC/RGB	Martell & Smith (2009)

Notes. ^(a) Although Hufnagel et al. (1995) found evidence of variations in the CN band strengths among the stars in their sample, they did not associate them with the existence of star-to-star abundance variations.

the LMC (Mucciarelli et al. 2008; Walker et al. 2011). For whatever processes may be responsible for the formation of multiple populations in stellar clusters, it appears that it is mainly related to their total mass, since only systems massive enough are able to retain the material ejected by the first generation, from which the subsequent populations are formed. Thus, there should be a mass limit below which clusters are unable to retain the ejected material and to form other stellar generations. According to dynamical models, this mass threshold is between $\sim 10^5$ and $10^6 M_\odot$ (e.g. Vesperini et al. 2010; Bekki 2011).

Constraining this limit from an observational point of view is challenging, since clusters lose a significant fraction of their initial masses during their lifetimes as a function of stellar evolution (e.g., material removed by supernova explosions or strong winds) and by tidal stripping. However, investigating less massive clusters helps to restrict the minimum mass required. In this paper, we have studied the behaviour of the CN and CH molecular band strengths in five OCs. Four of them (NGC 2158, NGC 2420, NGC 2682, and Berkeley 29) have unimodal CN and CH band distributions within the uncertainties, suggesting that they harbour a simple and chemically homogeneous population. In the case of the most massive of these clusters, Berkeley 29, the uncertainties are large enough to erase any sign of either bimodalities or broadening in the obtained distributions. In contrast, for NGC 7789, which has a mass similar to that of NGC 6791, we detected an anomalous spread in the distribution of the CN band strengths despite the large uncertainties in the index determinations for stars in this cluster.

To put our results in a general context, we used the age- M_V plane originally proposed by Carretta et al. (2010), where M_V is used as an indicator of the present-day total mass of the clusters. In Fig. 9, we have plotted several OCs with filled triangles. Those studied here and in Paper I are marked with open circles. The only OC where the existence of star-to-star variations in light element abundances have been confirmed, NGC 6791, has been coloured in green. The OC NGC 7789 has been coloured in magenta, since we have found evidence of the existence of chemical inhomogeneities in its stars. Systems with no signs of multiple populations, including those studied here and others previously investigated in the literature (Table 5), are coloured in red. Other interesting OCs that have not been studied yet are in grey. Star-to-star variations in light element abundances have been investigated in several OCs (e.g. de Silva et al. 2009; Smiljanic et al. 2009; Pancino et al. 2010a; Carrera & Pancino 2011). However, the number of stars analysed in each system is very small, and these have not been considered in our analysis. Following the same colour code, we have also plotted Galactic GCs (filled circles) and clusters in other external galaxies (open

stars with differing numbers of branches). These clusters and the references used are listed in Tables 6, 7 and 8. Lines of constant mass for different metallicities have been superimposed for reference. They have been computed from the simple stellar population models derived by Maraston (1998, 2005), assuming the Kroupa (2001) initial mass function¹.

No evidence of the existence of multiple populations has been reported for any of the five Galactic OCs studied with $M_V > -4$. In particular, we have analysed a statistically significant number of stars in three systems in this magnitude range (NGC 2158, NGC 2420, and NGC 2682), and we do not find any hint of chemical inhomogeneities. We conclude that clusters with $M_V > -4$ or masses lower than $\sim 10^4 M_\odot$ are not massive enough to form a second stellar generation.

Independent of their parent galaxy, almost all clusters older than ~ 9 Gyr are massive enough to host multiple stellar populations. Moreover, almost all these systems show star-to-star variations in light element abundances. The exceptions are the two Galactic GCs NGC 5466 and IC 4479, where no anomalous colour spreads in the ultraviolet have been detected by Lardo et al. (2011) or Walker et al. (2011). However, a similar result was found by Lardo et al. (2011) in NGC 2419, but an unnaturally wide RGB was later found by Beccari et al. (2013) using higher quality photometry. To our knowledge, the existence of star-to-star chemical abundance variations has not been studied until now in these two clusters.

SMC clusters with ages between 6 and 8 Gyr do not show unnatural features in their colour-magnitude diagrams to host multiple stellar populations despite their mass of $M_V \sim -8$. However, these features have been observed in clusters with ages younger than ~ 2.5 Gyr, in both the SMC (Glatt et al. 2008) and in the LMC (e.g., Milone et al. 2009; Piatti 2013). There are some exceptions, such as the massive cluster SL556 ($M_V \sim -9.5$) in the LMC (e.g. Bertelli et al. 2003). In contrast, star-to-star variations in light element abundances similar to those observed in GC have not been observed in intermediate-age LMC clusters (Mucciarelli et al. 2008, 2011). However, almost all the clusters analysed (NGC 1651, NGC 1866, and NGC 2173) also show no unnatural spreads in the MS turn-off region. The only exception is NGC 1783, where neither an anomalous MS turn-off (Milone et al. 2009) nor chemical inhomogeneities (Mucciarelli et al. 2008) have been initially reported, although a more accurate analysis of the MS turn-off region has revealed an unnatural spread (Platais et al. 2011). In any case, more determination of chemical abundances of stars in these clusters and in those with unnatural or multiple MS turn-offs are needed to confirm that clusters younger than ~ 2.5 Gyr are able to form multiple populations without the chemical inhomogeneities observed in old GC stars.

According to Fig. 9, the mass limit for forming multiple populations is between $M_V \sim -4$ and -5 . Unfortunately, the number of clusters studied in this range is small. Unnatural MS turn-offs have been observed in two LMC young clusters, SL 529 and SL 862, in this magnitude range as observed by Piatti (2013) and Milone et al. (2009), respectively. However, they have not been reported in slightly more massive clusters at $M_V \sim -5.5$. The only GC in this range is Palomar 12, which is associated with the Sagittarius dwarf spheroidal galaxy. As was explained in Sect. 1, star-to-star variations in light element abundances derived from high resolution spectroscopy have not been reported in this cluster (Cohen 2004). However, only four stars have been analysed.

¹ Available at http://www.icg.port.ac.uk/~maraston/Claudia's_Stellar_Population_Model.html

In the same way, Kayser et al. (2008) find no significant variations in the CN band strengths in their analysis of low-resolution spectra of 14 RGB stars in Palomar 12. In contrast, a clear bimodal anti-correlation of the CH and CN band strengths has been observed by Pancino et al. (2010b) by analysing 23 stars in the MS turn-off region. Since there is no agreement about the existence of chemical inhomogeneities in Palomar 12, we have coloured this cluster in magenta in Fig. 9. The other four systems in this magnitude range are OCs. Both chemical inhomogeneities in light element abundances that are derived from high-resolution spectroscopy (Geisler et al. 2012) and variations in the CN band strength that are measured in low-resolution spectra (Paper I) have been reported in the metal-rich OC NGC 6791. Moreover, this cluster shows unnaturally wide RGB and MS sequences (Carraro et al. 2006). However, star-to-star variations have not been observed in Berkeley 39 (Bragaglia et al. 2012). Although both systems have a similar present-day mass, it seems that NGC 6791 had a higher initial mass than Berkeley 29. The cluster NGC 6791 would have lost a significant fraction of its initial mass during repeated crossings of the denser parts of the disc. The remaining OCs NGC 7789 and Berkeley 29 are those studied here. Only nine stars have been analysed in the case of Berkeley 29. The uncertainties of the index determinations are large, which would erase any sign of bimodality or anomalous spread because of the low signal-to-noise ratio of the spectra used. In contrast, we found an anomalous spread in the case of NGC 7789, which is not explained by the uncertainties in the distribution of CN band strength at 3839 Å (Fig. 7). Although more studies are needed to confirm this result, it has a similar age and mass as the two LMC clusters where unnatural MS turn-offs have been reported.

Although much work remains to be done, the minimum present-day mass, according to Fig. 9 required for a cluster to be able to retain the material ejected by the first stellar generation and form subsequent populations is $\sim 10^4 M_\odot$. There are some clusters with a present-day mass similar to this that do not host multiple stellar populations. This may be because they have lost a low amount of mass during their lifetimes in comparison to other systems with similar present-day mass that were initially more massive. This value is lower than the mass threshold of $10^4\text{--}10^5 M_\odot$, as proposed by Mucciarelli et al. (2009); Carretta et al. (2010).

6. Summary

We have studied the strengths of the CN and CH bands at 3839, 4142 and 4300 Å in the MS stars of NGC 2158, NGC 2420, NGC 2682 (M 67), and Berkeley 29 and the RC objects of NGC 7789. For this analysis, we used low-resolution spectra ($R \sim 2000$) obtained in the framework of the SEGUE project within the SDSS.

Our main results are as follows:

- The molecular indices describe unimodal distributions for stars in NGC 2158, NGC 2420, NGC 2682, and Berkeley 29. All of them are well reproduced by single Gaussians with sigmas similar to the average uncertainties. Therefore, stars in these clusters have homogeneous abundances of C and N.
- Hints of bimodalities have been found in the distributions of the strength of the CN molecular band at 3839 Å for stars in NGC 7789. Although these features are smoothed when the uncertainties are considered, the generalized histograms still show a spread wider than that expected from the error bars. More analysis is needed to confirm the existence of

Fig. 9. Age versus M_V (as a proxy for mass) for Galactic OCs (triangles) and GCs (filled circles). Clusters in other galaxies have been marked with stars with differing numbers of branches: LMC (four), Small Magellanic Cloud (SMC, five), Sagittarius (six), and Fornax (seven). Clusters for which either multiple sequences in the colour–magnitude diagrams, chemical inhomogeneities, or both have been detected are in green, whereas clusters without either are in red. In magenta are clusters for which there are doubts about the existence of chemical inhomogeneities. Clusters not properly studied are in grey. Clusters studied here are encircled. Lines of constant mass for different metallicities have been superimposed (See text for detail).

star-to-star variations in the CN strengths of stars in this cluster because of the small number of objects studied here.

- We have discussed our results in the framework of the formation of multiple stellar populations in stellar clusters of different ages and environments. We find that the present-day mass limit above which a cluster may be able to host multiple stellar populations is $\sim 10^4 M_\odot$.

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Table 2. Index measurements for the sample stars.

Cluster	Plate ^a	Fiber ^a	RA	Dec	<i>g</i>	<i>V</i>	ID _{phot} ^b	<i>S</i> 3839 _H	<i>S</i> 3839 _N	<i>S</i> 4142	<i>CH</i> 4300
NGC 2158	2912	409	06 07 10.96	+24 09 33.50		17.51	899	-0.50 ± 0.03	-0.28 ± 0.03	-0.32 ± 0.03	-0.48 ± 0.03
NGC 2158	2912	416	06 07 14.18	+24 08 8.80		17.53	919	-0.49 ± 0.03	-0.28 ± 0.03	-0.33 ± 0.03	-0.48 ± 0.03
NGC 2158	2912	417	06 07 14.25	+24 10 13.00		17.86	1143	-0.49 ± 0.04	-0.26 ± 0.04	-0.32 ± 0.04	-0.48 ± 0.04
NGC 2158	2912	442	06 07 28.80	+24 09 21.90		17.16	693	-0.49 ± 0.03	-0.25 ± 0.03	-0.33 ± 0.03	-0.49 ± 0.03
NGC 2158	2912	444	06 07 32.53	+24 10 9.60		17.29	754	-0.53 ± 0.03	-0.30 ± 0.03	-0.33 ± 0.03	-0.48 ± 0.03
NGC 2158	2912	446	06 07 34.43	+24 09 20.00		18.22	1446	-0.51 ± 0.04	-0.32 ± 0.04	-0.34 ± 0.04	-0.44 ± 0.04
NGC 2158	2912	450	06 07 27.54	+24 10 23.50		16.84	438	-0.51 ± 0.02	-0.29 ± 0.02	-0.33 ± 0.02	-0.48 ± 0.02
NGC 2158	2912	453	06 07 24.35	+24 08 36.30		17.53	928	-0.46 ± 0.03	-0.24 ± 0.03	-0.33 ± 0.03	-0.48 ± 0.03
NGC 2158	2912	459	06 07 14.77	+24 09 6.90		18.12	1365	-0.54 ± 0.04	-0.26 ± 0.04	-0.35 ± 0.04	-0.45 ± 0.04
NGC 2158	2912	462	06 07 5.84	+24 02 58.80		17.82	1139	-0.53 ± 0.03	-0.29 ± 0.03	-0.33 ± 0.03	-0.48 ± 0.03
NGC 2158	2912	464	06 07 1.56	+24 07 28.80		17.53	921	-0.54 ± 0.03	-0.31 ± 0.03	-0.32 ± 0.03	-0.48 ± 0.03
NGC 2158	2912	480	06 07 1.97	+24 03 43.20		18.17	1364	-0.48 ± 0.04	-0.26 ± 0.04	-0.34 ± 0.04	-0.49 ± 0.04
NGC 2158	2912	482	06 07 13.03	+24 05 19.30		17.46	864	-0.52 ± 0.03	-0.27 ± 0.03	-0.33 ± 0.03	-0.48 ± 0.03
NGC 2158	2912	483	06 07 16.86	+24 03 7.10		16.96	552	-0.51 ± 0.02	-0.29 ± 0.02	-0.33 ± 0.02	-0.47 ± 0.02
NGC 2158	2912	484	06 07 15.38	+24 04 5.50		17.10	635	-0.53 ± 0.03	-0.28 ± 0.03	-0.33 ± 0.03	-0.47 ± 0.03
NGC 2158	2912	485	06 07 10.35	+24 03 36.20		17.15	660	-0.51 ± 0.03	-0.28 ± 0.03	-0.33 ± 0.03	-0.47 ± 0.03
NGC 2158	2912	487	06 07 6.84	+24 04 57.60		16.81	449	-0.53 ± 0.02	-0.31 ± 0.02	-0.33 ± 0.02	-0.48 ± 0.02
NGC 2158	2912	488	06 07 9.35	+24 08 40.50		17.68	1014	-0.46 ± 0.03	-0.25 ± 0.03	-0.33 ± 0.03	-0.47 ± 0.03
NGC 2158	2912	489	06 07 9.62	+24 07 8.10		17.13	673	-0.53 ± 0.02	-0.29 ± 0.03	-0.33 ± 0.03	-0.47 ± 0.02
NGC 2158	2912	494	06 07 10.78	+24 06 13.20		17.02	580	-0.50 ± 0.02	-0.26 ± 0.02	-0.32 ± 0.02	-0.47 ± 0.02
NGC 2158	2912	498	06 07 6.11	+24 07 37.80		17.91	1163	-0.49 ± 0.03	-0.23 ± 0.03	-0.33 ± 0.03	-0.44 ± 0.03
NGC 2158	2912	502	06 07 26.11	+24 07 9.80		17.60	980	-0.51 ± 0.03	-0.28 ± 0.03	-0.34 ± 0.03	-0.48 ± 0.03
NGC 2158	2912	503	06 07 18.28	+24 07 8.30		17.21	735	-0.50 ± 0.03	-0.27 ± 0.03	-0.32 ± 0.03	-0.48 ± 0.03
NGC 2158	2912	505	06 07 28.43	+24 08 7.20		17.33	780	-0.51 ± 0.03	-0.26 ± 0.03	-0.33 ± 0.03	-0.48 ± 0.03
NGC 2158	2912	507	06 07 15.40	+24 06 6.40		17.35	811	-0.53 ± 0.03	-0.30 ± 0.03	-0.33 ± 0.03	-0.48 ± 0.03
NGC 2158	2912	516	06 07 18.67	+24 05 28.20		17.20	718	-0.52 ± 0.03	-0.29 ± 0.03	-0.33 ± 0.03	-0.47 ± 0.03
NGC 2158	2912	519	06 07 25.35	+24 04 20.90		18.05	1320	-0.53 ± 0.03	-0.27 ± 0.03	-0.34 ± 0.03	-0.47 ± 0.03
NGC 2158	2912	541	06 07 41.07	+24 05 11.20		16.84	462	-0.51 ± 0.02	-0.28 ± 0.02	-0.33 ± 0.02	-0.47 ± 0.02
NGC 2158	2912	542	06 07 36.73	+24 04 47.90		16.70	401	-0.51 ± 0.02	-0.27 ± 0.02	-0.33 ± 0.02	-0.48 ± 0.02
NGC 2158	2912	545	06 07 32.89	+24 08 5.70		17.14	656	-0.54 ± 0.03	-0.29 ± 0.03	-0.34 ± 0.03	-0.47 ± 0.03
NGC 2158	2912	548	06 07 39.51	+24 03 1.60		16.74	424	-0.52 ± 0.02	-0.28 ± 0.02	-0.33 ± 0.02	-0.48 ± 0.02
NGC 2158	2912	549	06 07 32.40	+24 05 28.90		17.30	776	-0.50 ± 0.03	-0.27 ± 0.03	-0.33 ± 0.03	-0.47 ± 0.03
NGC 2158	2912	550	06 07 38.62	+24 06 4.20		16.59	355	-0.50 ± 0.02	-0.26 ± 0.02	-0.33 ± 0.02	-0.47 ± 0.02
NGC 2158	2912	556	06 07 30.62	+24 03 3.00		16.99	576	-0.51 ± 0.02	-0.28 ± 0.02	-0.33 ± 0.02	-0.48 ± 0.02
NGC 2158	2912	558	06 07 40.99	+24 04 3.70		17.16	694	-0.51 ± 0.03	-0.29 ± 0.03	-0.33 ± 0.03	-0.48 ± 0.03
NGC 2420	2078	111	07 38 56.10	+21 31 58.95	17.23		346201019	-0.42 ± 0.04	-0.17 ± 0.04	-0.40 ± 0.04	-0.40 ± 0.04
NGC 2420	2078	114	07 39 3.18	+21 27 2.33	16.89		346200251	-0.43 ± 0.03	-0.19 ± 0.04	-0.37 ± 0.03	-0.42 ± 0.03
NGC 2420	2078	142	07 38 41.15	+21 28 27.97	17.36		346201004	-0.37 ± 0.04	-0.11 ± 0.05	-0.39 ± 0.04	-0.37 ± 0.04
NGC 2420	2078	149	07 38 34.33	+21 26 55.42	15.17		346201001	-0.54 ± 0.02	-0.29 ± 0.02	-0.33 ± 0.02	-0.50 ± 0.02
NGC 2420	2078	151	07 38 41.38	+21 32 22.35	16.83		346201518	-0.43 ± 0.03	-0.20 ± 0.03	-0.37 ± 0.03	-0.41 ± 0.03
NGC 2420	2078	156	07 38 48.75	+21 30 57.37	16.91		346201098	-0.46 ± 0.03	-0.19 ± 0.04	-0.37 ± 0.03	-0.41 ± 0.03
NGC 2420	2078	157	07 38 36.99	+21 31 45.51	17.21		346201576	-0.41 ± 0.04	-0.12 ± 0.04	-0.38 ± 0.04	-0.40 ± 0.04
NGC 2420	2078	159	07 38 41.00	+21 27 2.47	15.40		346200836	-0.53 ± 0.02	-0.29 ± 0.02	-0.33 ± 0.02	-0.50 ± 0.02
NGC 2420	2078	161	07 38 17.10	+21 32 36.24	15.12		346202469	-0.53 ± 0.02	-0.28 ± 0.02	-0.33 ± 0.02	-0.50 ± 0.02
NGC 2420	2078	166	07 38 19.69	+21 31 10.71	15.80		346202104	-0.52 ± 0.03	-0.27 ± 0.03	-0.35 ± 0.03	-0.48 ± 0.03
NGC 2420	2078	167	07 38 24.42	+21 26 59.25	17.11		346201291	-0.41 ± 0.04	-0.14 ± 0.04	-0.39 ± 0.04	-0.39 ± 0.04
NGC 2420	2078	172	07 38 16.53	+21 30 17.67	17.49		346202077	-0.35 ± 0.04	-0.10 ± 0.05	-0.38 ± 0.04	-0.37 ± 0.04
NGC 2420	2078	176	07 38 34.00	+21 36 13.74	15.09		346202429	-0.53 ± 0.02	-0.28 ± 0.02	-0.33 ± 0.02	-0.50 ± 0.02
NGC 2420	2078	179	07 38 17.30	+21 34 9.55	15.33		288801337	-0.51 ± 0.02	-0.28 ± 0.02	-0.33 ± 0.02	-0.50 ± 0.02
NGC 2420	2078	182	07 38 11.00	+21 28 53.95	14.97		346202051	-0.54 ± 0.02	-0.29 ± 0.02	-0.34 ± 0.02	-0.50 ± 0.02
NGC 2420	2078	186	07 38 7.90	+21 29 48.20	15.29		346202322	-0.52 ± 0.02	-0.29 ± 0.02	-0.33 ± 0.02	-0.49 ± 0.02
NGC 2420	2078	192	07 38 4.86	+21 30 30.20	17.26		288801191	-0.38 ± 0.04	-0.10 ± 0.04	-0.38 ± 0.04	-0.39 ± 0.04
NGC 2420	2078	195	07 38 1.92	+21 28 50.40	15.56		351300099	-0.53 ± 0.02	-0.29 ± 0.03	-0.33 ± 0.03	-0.49 ± 0.02
NGC 2420	2078	197	07 38 12.27	+21 34 18.23	17.28		288801600	-0.37 ± 0.04	-0.11 ± 0.04	-0.36 ± 0.04	-0.40 ± 0.04
NGC 2420	2078	199	07 38 15.23	+21 25 8.35	16.06		346201322	-0.51 ± 0.03	-0.27 ± 0.03	-0.34 ± 0.03	-0.47 ± 0.03
NGC 2420	2078	223	07 37 33.71	+21 31 23.72	16.04		351301606	-0.50 ± 0.03	-0.25 ± 0.03	-0.34 ± 0.03	-0.46 ± 0.03
NGC 2420	2078	224	07 37 51.33	+21 32 38.16	14.88		351301230	-0.53 ± 0.02	-0.28 ± 0.02	-0.33 ± 0.02	-0.50 ± 0.02
NGC 2420	2078	227	07 37 48.30	+21 28 8.04	17.06		351300628	-0.40 ± 0.04	-0.15 ± 0.04	-0.38 ± 0.04	-0.40 ± 0.04
NGC 2420	2078	235	07 37 57.65	+21 32 54.41	17.39		351301082	-0.30 ± 0.04	-0.05 ± 0.05	-0.39 ± 0.04	-0.37 ± 0.04
NGC 2420	2078	431	07 37 53.98	+21 39 46.99	14.80		351302033	-0.52 ± 0.02	-0.27 ± 0.02	-0.32 ± 0.02	-0.49 ± 0.02
NGC 2420	2078	462	07 38 12.24	+21 44 27.07	16.45		288802992	-0.47 ± 0.03	-0.21 ± 0.03	-0.35 ± 0.03	-0.45 ± 0.03
NGC 2420	2078	470	07 38 5.14	+21 42 37.32	17.38		288802976	-0.35 ± 0.04	-0.07 ± 0.04	-0.38 ± 0.04	-0.37 ± 0.04
NGC 2420	2078	471	07 38 7.28	+21 36 53.64	16.48		288802179	-0.49 ± 0.03	-0.22 ± 0.03	-0.34 ± 0.03	-0.44 ± 0.03

Notes. ^(a) Plate and fiber uniquely identify the spectrum used in the analysis for each star in the SDSS III database. ^(b) ID_{phot} identifies the star in the photometry used. For NGC 2420 and NGC 2682 the first four numbers identify the plate in [An et al. \(2008\)](#).

Table 2. continued.

Cluster	Plate ^a	Fiber ^a	RA	Dec	<i>g</i>	<i>V</i>	ID _{phot} ^b	<i>S</i> 3839 _H	<i>S</i> 3839 _N	<i>S</i> 4142	<i>CH</i> 4300
NGC 2420	2078	472	07 38 19.73	+21 35 54.33	14.77		288801559	-0.52 ± 0.02	-0.27 ± 0.02	-0.33 ± 0.02	-0.50 ± 0.02
NGC 2420	2078	473	07 38 5.30	+21 36 3.27	16.68		288802135	-0.44 ± 0.03	-0.19 ± 0.03	-0.36 ± 0.03	-0.43 ± 0.03
NGC 2420	2078	480	07 38 12.43	+21 39 50.45	17.42		288802411	-0.31 ± 0.04	-0.10 ± 0.04	-0.38 ± 0.04	-0.37 ± 0.04
NGC 2420	2078	485	07 38 25.29	+21 41 38.84	16.95		288802252	-0.37 ± 0.03	-0.12 ± 0.04	-0.38 ± 0.03	-0.39 ± 0.03
NGC 2420	2078	487	07 38 22.50	+21 44 4.94	17.43		288802638	-0.37 ± 0.04	-0.12 ± 0.04	-0.38 ± 0.04	-0.40 ± 0.04
NGC 2420	2078	496	07 38 24.69	+21 36 52.45	17.05		288801513	-0.40 ± 0.04	-0.17 ± 0.04	-0.37 ± 0.04	-0.39 ± 0.04
NGC 2420	2078	510	07 38 50.89	+21 37 3.58	17.12		346201907	-0.41 ± 0.03	-0.15 ± 0.04	-0.37 ± 0.03	-0.39 ± 0.03
NGC 2420	2078	511	07 38 38.44	+21 36 47.52	15.35		346202348	-0.52 ± 0.02	-0.28 ± 0.02	-0.33 ± 0.02	-0.49 ± 0.02
NGC 2420	2078	512	07 38 41.28	+21 37 48.23	15.78		346202417	-0.50 ± 0.02	-0.26 ± 0.03	-0.33 ± 0.03	-0.49 ± 0.02
NGC 2420	2078	514	07 38 52.55	+21 34 48.75	16.99		346201507	-0.42 ± 0.03	-0.17 ± 0.04	-0.38 ± 0.03	-0.40 ± 0.03
NGC 2420	2078	515	07 38 48.16	+21 36 20.27	16.76		346201883	-0.44 ± 0.03	-0.19 ± 0.03	-0.35 ± 0.03	-0.42 ± 0.03
NGC 2420	2078	516	07 38 34.09	+21 39 5.63	16.36		288801503	-0.47 ± 0.03	-0.22 ± 0.03	-0.35 ± 0.03	-0.44 ± 0.03
NGC 2420	2078	519	07 38 52.83	+21 36 2.34	17.33		346201678	-0.34 ± 0.04	-0.09 ± 0.04	-0.38 ± 0.04	-0.37 ± 0.04
NGC 2420	2078	520	07 38 45.62	+21 34 51.38	16.66		346201744	-0.46 ± 0.03	-0.20 ± 0.03	-0.36 ± 0.03	-0.42 ± 0.03
NGC 2420	2078	548	07 39 5.16	+21 41 5.29	14.97		346202059	-0.52 ± 0.02	-0.28 ± 0.02	-0.33 ± 0.02	-0.51 ± 0.02
NGC 2420	2078	554	07 38 56.96	+21 40 56.87	15.00		346202350	-0.52 ± 0.02	-0.27 ± 0.02	-0.33 ± 0.02	-0.50 ± 0.02
NGC 2420	2078	560	07 39 9.67	+21 36 55.21	17.34		346201266	-0.35 ± 0.04	-0.10 ± 0.04	-0.39 ± 0.04	-0.37 ± 0.04
NGC 2420	2079	181	07 38 11.00	+21 28 53.95	14.97		346202051	-0.52 ± 0.02	-0.28 ± 0.02	-0.34 ± 0.02	-0.50 ± 0.02
NGC 2420	2079	483	07 38 19.73	+21 35 54.33	14.77		288801559	-0.52 ± 0.02	-0.28 ± 0.02	-0.33 ± 0.02	-0.50 ± 0.02
NGC 2682	2667	372	08 50 46.88	+11 53 52.66	15.68		597200953	-0.08 ± 0.04	0.21 ± 0.04	-0.36 ± 0.04	-0.32 ± 0.04
NGC 2682	2667	378	08 50 45.60	+11 55 35.66	16.24		597201129	-0.01 ± 0.04	0.33 ± 0.05	-0.34 ± 0.04	-0.30 ± 0.04
NGC 2682	2667	404	08 51 0.77	+11 53 11.41	15.09		597200801	-0.13 ± 0.03	0.11 ± 0.04	-0.36 ± 0.03	-0.35 ± 0.03
NGC 2682	2667	406	08 50 48.13	+11 54 47.64	14.33		597201043	-0.32 ± 0.03	-0.09 ± 0.03	-0.36 ± 0.03	-0.39 ± 0.03
NGC 2682	2667	407	08 50 56.34	+11 51 29.28	14.35		597200622	-0.33 ± 0.03	-0.10 ± 0.03	-0.36 ± 0.03	-0.39 ± 0.03
NGC 2682	2667	408	08 50 58.51	+11 59 39.37	14.48		597201464	-0.27 ± 0.03	-0.03 ± 0.03	-0.36 ± 0.03	-0.38 ± 0.03
NGC 2682	2667	409	08 51 5.83	+11 53 10.62	15.38		597200770	-0.07 ± 0.04	0.20 ± 0.04	-0.36 ± 0.03	-0.33 ± 0.03
NGC 2682	2667	410	08 50 57.08	+11 56 50.64	15.28		597201171	-0.11 ± 0.04	0.15 ± 0.04	-0.37 ± 0.03	-0.34 ± 0.03
NGC 2682	2667	411	08 51 12.23	+11 47 14.80	15.47		600401489	-0.07 ± 0.04	0.20 ± 0.04	-0.37 ± 0.03	-0.33 ± 0.03
NGC 2682	2667	412	08 50 56.68	+11 49 54.66	14.94		597200432	-0.18 ± 0.03	0.06 ± 0.04	-0.37 ± 0.03	-0.36 ± 0.03
NGC 2682	2667	413	08 51 4.51	+11 51 45.94	14.31		597200598	-0.31 ± 0.03	-0.07 ± 0.03	-0.36 ± 0.03	-0.39 ± 0.03
NGC 2682	2667	415	08 50 48.03	+11 49 41.56	14.81		597200467	-0.18 ± 0.03	0.05 ± 0.04	-0.37 ± 0.03	-0.36 ± 0.03
NGC 2682	2667	417	08 51 1.62	+11 56 16.12	15.25		597201101	-0.12 ± 0.03	0.14 ± 0.04	-0.36 ± 0.03	-0.34 ± 0.03
NGC 2682	2667	418	08 51 0.82	+11 48 52.82	14.90		597200266	-0.19 ± 0.03	0.04 ± 0.04	-0.36 ± 0.03	-0.36 ± 0.03
NGC 2682	2667	419	08 50 58.36	+11 58 14.61	14.76		597201301	-0.22 ± 0.03	0.02 ± 0.03	-0.37 ± 0.03	-0.36 ± 0.03
NGC 2682	2667	420	08 51 9.93	+11 46 16.86	14.83		600401385	-0.22 ± 0.03	0.01 ± 0.03	-0.37 ± 0.03	-0.36 ± 0.03
NGC 2682	2667	441	08 51 13.00	+11 57 0.69	14.71		597201113	-0.27 ± 0.03	-0.03 ± 0.03	-0.37 ± 0.03	-0.37 ± 0.03
NGC 2682	2667	445	08 51 7.97	+11 58 53.04	15.04		597201305	-0.16 ± 0.03	0.08 ± 0.04	-0.37 ± 0.03	-0.35 ± 0.03
NGC 2682	2667	451	08 51 12.30	+11 54 22.86	14.41		597200853	-0.29 ± 0.03	-0.05 ± 0.03	-0.36 ± 0.03	-0.37 ± 0.03
NGC 2682	2667	453	08 51 22.17	+11 48 27.93	16.13		600401584	0.02 ± 0.04	0.31 ± 0.04	-0.35 ± 0.04	-0.31 ± 0.04
NGC 2682	2667	454	08 51 21.77	+11 51 42.05	14.32		597200466	-0.30 ± 0.03	-0.07 ± 0.03	-0.36 ± 0.03	-0.38 ± 0.03
NGC 2682	2667	455	08 51 42.80	+11 59 30.59	14.28		597201165	-0.34 ± 0.03	-0.10 ± 0.03	-0.36 ± 0.03	-0.39 ± 0.03
NGC 2682	2667	457	08 51 37.58	+11 56 44.28	14.69		597200931	-0.26 ± 0.03	-0.01 ± 0.03	-0.37 ± 0.03	-0.37 ± 0.03
NGC 2682	2667	459	08 51 15.06	+11 49 21.11	14.38		597200214	-0.32 ± 0.03	-0.08 ± 0.03	-0.37 ± 0.03	-0.38 ± 0.03
NGC 2682	2667	460	08 51 9.16	+11 57 0.12	14.82		597201130	-0.19 ± 0.03	0.04 ± 0.04	-0.37 ± 0.03	-0.36 ± 0.03
NGC 2682	2667	478	08 50 47.14	+11 42 54.82	14.40		600401125	-0.29 ± 0.03	-0.06 ± 0.03	-0.37 ± 0.03	-0.38 ± 0.03
NGC 2682	2667	479	08 50 52.31	+11 45 3.70	14.91		600401367	-0.19 ± 0.03	0.06 ± 0.04	-0.37 ± 0.03	-0.36 ± 0.03
NGC 2682	2667	481	08 51 10.79	+11 39 50.80	14.94		600400554	-0.18 ± 0.03	0.06 ± 0.04	-0.37 ± 0.03	-0.36 ± 0.03
NGC 2682	2667	485	08 51 2.06	+11 45 19.11	15.29		600401322	-0.07 ± 0.04	0.19 ± 0.04	-0.36 ± 0.03	-0.34 ± 0.03
NGC 2682	2667	486	08 51 0.68	+11 40 41.36	15.73		600400741	-0.03 ± 0.04	0.25 ± 0.04	-0.36 ± 0.03	-0.33 ± 0.03
NGC 2682	2667	487	08 51 5.77	+11 43 46.88	14.33		600401088	-0.25 ± 0.03	0.00 ± 0.03	-0.37 ± 0.03	-0.36 ± 0.03
NGC 2682	2667	490	08 51 17.21	+11 42 36.55	14.83		600400848	-0.20 ± 0.03	0.03 ± 0.03	-0.37 ± 0.03	-0.36 ± 0.03
NGC 2682	2667	505	08 51 21.78	+11 44 4.95	14.46		600401013	-0.28 ± 0.03	-0.03 ± 0.03	-0.36 ± 0.03	-0.37 ± 0.03
NGC 2682	2667	507	08 51 24.69	+11 43 6.26	15.02		600400853	-0.13 ± 0.03	0.11 ± 0.04	-0.37 ± 0.03	-0.34 ± 0.03
NGC 2682	2667	508	08 51 25.23	+11 38 16.02	15.58		600400307	-0.05 ± 0.04	0.21 ± 0.04	-0.36 ± 0.03	-0.32 ± 0.03
NGC 2682	2667	522	08 52 0.41	+11 56 6.81	14.62		597200725	-0.26 ± 0.03	-0.02 ± 0.03	-0.36 ± 0.03	-0.37 ± 0.03
NGC 2682	2667	531	08 51 56.59	+11 47 24.89	14.65		600401168	-0.27 ± 0.03	-0.03 ± 0.03	-0.37 ± 0.03	-0.36 ± 0.03
NGC 2682	2667	533	08 51 58.80	+11 48 14.67	15.97		600401257	-0.01 ± 0.04	0.28 ± 0.04	-0.35 ± 0.04	-0.32 ± 0.04
NGC 2682	2667	537	08 51 58.77	+11 50 2.37	14.61		600401492	-0.26 ± 0.03	-0.03 ± 0.03	-0.37 ± 0.03	-0.37 ± 0.03
NGC 2682	2667	539	08 52 4.54	+11 58 48.53	16.13		597200981	-0.02 ± 0.04	0.27 ± 0.04	-0.35 ± 0.04	-0.31 ± 0.04
NGC 2682	2667	540	08 51 58.60	+11 52 15.13	15.65		597200253	-0.07 ± 0.04	0.21 ± 0.04	-0.36 ± 0.03	-0.33 ± 0.03
NGC 2682	2667	546	08 52 9.62	+11 46 46.08	14.27		600400989	-0.34 ± 0.03	-0.11 ± 0.03	-0.36 ± 0.03	-0.39 ± 0.03
NGC 2682	2667	552	08 52 6.43	+11 40 14.83	15.60		600400265	-0.10 ± 0.04	0.20 ± 0.04	-0.38 ± 0.03	-0.32 ± 0.03
NGC 2682	2667	575	08 52 15.45	+11 53 1.31	14.77		597200224	-0.24 ± 0.03	-0.00 ± 0.03	-0.36 ± 0.03	-0.36 ± 0.03
NGC 2682	2667	576	08 52 22.22	+11 49 2.88	15.24		600401184	-0.10 ± 0.04	0.16 ± 0.04	-0.37 ± 0.03	-0.33 ± 0.03
NGC 2682	2667	579	08 52 15.82	+11 46 31.97	15.31		600400903	-0.10 ± 0.03	0.16 ± 0.04	-0.36 ± 0.03	-0.34 ± 0.03
NGC 7789	2377	162	23 57 25.01	+56 38 36.33		12.84	8383	0.32 ± 0.06	0.60 ± 0.06	-0.16 ± 0.05	-0.30 ± 0.05

Table 2. continued.

Cluster	Plate ^a	Fiber ^a	RA	Dec	<i>g</i>	<i>V</i>	ID _{phot} ^b	<i>S</i> 3839 _H	<i>S</i> 3839 _N	<i>S</i> 4142	<i>CH</i> 4300
NGC 7789	2377	171	23 57 28.39	+56 41 31.16	12.89	8647		0.57 ± 0.06	0.95 ± 0.07	−0.17 ± 0.05	−0.31 ± 0.05
NGC 7789	2377	175	23 57 24.18	+56 39 36.17	12.91	8316		0.27 ± 0.06	0.60 ± 0.06	−0.20 ± 0.05	−0.32 ± 0.05
NGC 7789	2377	176	23 57 32.79	+56 40 19.71	13.06	9048		0.38 ± 0.06	0.67 ± 0.06	−0.18 ± 0.05	−0.31 ± 0.05
NGC 7789	2377	191	23 56 57.27	+56 36 55.12	12.98	5862		0.36 ± 0.06	0.69 ± 0.06	−0.15 ± 0.05	−0.29 ± 0.05
NGC 7789	2377	439	23 56 40.98	+56 41 47.08	13.26	4485		0.35 ± 0.06	0.64 ± 0.06	−0.15 ± 0.05	−0.30 ± 0.05
NGC 7789	2377	466	23 56 29.53	+56 48 39.93	13.17	3573		0.30 ± 0.06	0.57 ± 0.06	−0.11 ± 0.05	−0.29 ± 0.05
NGC 7789	2377	467	23 56 29.31	+56 45 43.20	13.40	3569		0.08 ± 0.06	0.46 ± 0.06	−0.24 ± 0.05	−0.30 ± 0.05
NGC 7789	2377	488	23 57 18.48	+56 50 27.10	13.01	7714		0.30 ± 0.06	0.67 ± 0.06	−0.12 ± 0.05	−0.29 ± 0.05
NGC 7789	2377	494	23 56 44.52	+56 42 53.60	13.16	4751		0.35 ± 0.06	0.70 ± 0.06	−0.11 ± 0.05	−0.30 ± 0.05
NGC 7789	2377	503	23 57 41.35	+56 42 7.47	12.87	9831		0.27 ± 0.06	0.63 ± 0.06	−0.12 ± 0.05	−0.29 ± 0.05
NGC 7789	2377	560	23 58 46.52	+56 49 52.63	12.79	14471		0.25 ± 0.06	0.54 ± 0.06	−0.17 ± 0.05	−0.32 ± 0.05
Be29	3335	154	06 53 19.01	+16 57 2.10	19.24	574		−0.57 ± 0.09	−0.38 ± 0.09	−0.34 ± 0.09	−0.50 ± 0.09
Be29	3335	166	06 53 2.10	+16 52 34.86	19.33	177		−0.58 ± 0.09	−0.34 ± 0.09	−0.33 ± 0.09	−0.51 ± 0.09
Be29	3335	461	06 52 51.65	+16 56 11.20	19.72	1505		−0.36 ± 0.12	−0.11 ± 0.12	−0.36 ± 0.12	−0.45 ± 0.12
Be29	3335	463	06 53 0.58	+16 54 41.91	19.77	134		−0.52 ± 0.12	−0.19 ± 0.13	−0.31 ± 0.13	−0.50 ± 0.12
Be29	3335	483	06 53 12.31	+16 55 31.61	19.52	819		−0.53 ± 0.09	−0.29 ± 0.09	−0.32 ± 0.09	−0.48 ± 0.09
Be29	3335	484	06 53 6.11	+16 56 47.64	19.82	326		−0.55 ± 0.12	−0.25 ± 0.13	−0.37 ± 0.13	−0.51 ± 0.12
Be29	3335	485	06 53 5.20	+16 54 42.44	19.04	734		−0.49 ± 0.07	−0.30 ± 0.07	−0.33 ± 0.07	−0.50 ± 0.07
Be29	3335	501	06 53 11.29	+16 56 31.53	19.33	473		−0.45 ± 0.09	−0.26 ± 0.09	−0.31 ± 0.09	−0.51 ± 0.09
Be29	3335	503	06 53 15.49	+16 56 21.81	19.98	840		−0.53 ± 0.13	−0.27 ± 0.14	−0.32 ± 0.14	−0.48 ± 0.13

Table 4. Coefficients of the linear or quadratic fit used to construct the corrected pseudo-indices and marked as dashed lines in Figs. 4–8, respectively.

Index	<i>a</i>	<i>b</i>	<i>c</i>
NGC 2158			
<i>S</i> 3839 _H	-0.59 ± 0.19	0.004 ± 0.011	
<i>S</i> 3839 _N	-0.31 ± 0.22	0.001 ± 0.013	
<i>S</i> 4142	-0.22 ± 0.06	-0.006 ± 0.003	
<i>CH</i> 4300	-0.60 ± 0.14	0.007 ± 0.008	
NGC 2420			
<i>S</i> 3839 _H	8.85 ± 1.74	-1.22 ± 0.22	0.040 ± 0.007
<i>S</i> 3839 _N	9.55 ± 1.61	-1.28 ± 0.20	0.042 ± 0.006
<i>S</i> 4142	-2.14 ± 0.70	0.24 ± 0.09	-0.008 ± 0.003
<i>CH</i> 4300	2.23 ± 0.87	-0.39 ± 0.11	0.014 ± 0.003
NGC 2682			
<i>S</i> 3839 _H	-13.60 ± 244.49	1.59 ± 32.65	-0.05 ± 1.09
<i>S</i> 3839 _N	-8.56 ± 13.29	0.92 ± 1.82	-0.02 ± 0.06
<i>S</i> 4142	2.81 ± 9.55	-0.42 ± 0.13	0.01 ± 0.04
<i>CH</i> 4300	-2.34 ± 6.27	0.22 ± 0.80	-0.006 ± 0.028
NGC 7789			
<i>S</i> 3839 _H	0.11 ± 3.74	0.15 ± 2.84	
<i>S</i> 3839 _N	0.45 ± 3.96	0.15 ± 3.01	
<i>S</i> 4142	-1.33 ± 0.96	0.89 ± 0.73	
<i>CH</i> 4300	-0.54 ± 0.28	0.18 ± 0.22	
Berkeley 29			
<i>S</i> 3839 _H	-0.39 ± 6.90	-0.00 ± 0.35	
<i>S</i> 3839 _N	-3.24 ± 4.16	0.15 ± 0.21	
<i>S</i> 4142	-0.00 ± 1.37	-0.02 ± 0.07	
<i>CH</i> 4300	-0.98 ± 1.41	0.02 ± 0.07	

Table 6. Open clusters used in Fig. 9.

Cluster	M_V	Age (Gyr)	Notes	References
NGC 188	-2.86	6.30	1	1, 2
NGC 752	-2.85	1.24	1	2, 3
NGC 1193	-3.00	4.23	0	1, 2
NGC 1798	-3.46	1.40	0	1, 5
NGC 2099	-4.91	0.40	0	4, 6
NGC 2158	-2.81	1.91	1	1, 2
NGC 2204	-4.65	1.86	0	1
NGC 2243	-2.67	4.66	0	1, 2
NGC 2266	-3.83	0.70	0	1, 5
NGC 2420	-3.44	2.20	1	1, 2
NGC 2506	-4.49	2.14	0	2, 4
NGC 2660	-3.87	0.73	0	1, 2
NGC 2682	-3.16	4.30	1	1, 2
NGC 6253	-2.68	5.00	0	1
NGC 6705	-6.00	0.25	0	1, 10
NGC 6791	-4.14	8.00	9	1
NGC 6819	-4.90	2.91	0	2, 7
NGC 7142	-0.73	4.04	0	2, 8
NGC 7789	-5.04	1.80	1	2, 4
Berkeley 14	-4.07	1.58	0	1
Berkeley 18	-4.90	5.69	0	1, 2
Berkeley 21	-3.41	2.18	0	1, 2
Berkeley 22	-3.27	4.26	0	1, 2
Berkeley 29	-4.64	4.34	1	1, 2
Berkeley 31	-2.57	5.32	0	1, 2
Berkeley 32	-2.97	5.91	0	1, 2
Berkeley 39	-4.28	7.00	1	1, 2
Berkeley 54	-3.21	7.27	0	2
Berkeley 99	-3.66	3.16	0	1
IC 1311	-3.90	1.58	0	1
IC 4651	-2.89	3.31	0	1
Colinder 261	-2.87	8.00	0	1, 2
Pismis 19	-4.59	1.09	0	1
Praesepe	-2.69	0.70	0	2, 8
To2	-7.48	2.13	0	2, 9
Trumpler 5	-5.06	5.67	0	1, 2

Notes. 0) Not studied; 1) No multiple sequences, chemical inhomogeneities not studied; 2) Neither multiple sequences nor chemical inhomogeneities; 3) No chemical inhomogeneities, multiple sequences not studied; 4) Doubtful; 5) Multiple sequences, no chemical inhomogeneities; 6) Chemical inhomogeneities, no multiple sequences; 7) Chemical inhomogeneities, multiple sequences not studied; 8) Multiple sequence, chemical inhomogeneities not studied; 9) Both multiple sequences and chemical inhomogeneities.

References. (1) Lata et al. (2002); (2) Salaris et al. (2004); (3) Spassova & Baev (1985); (4) Kharchenko et al. (2009); (5) Carrera (2012a); (6) Pancino et al. (2010a); (7) Sagar et al. (1983); (8) Gray (1965); (9) Pandey et al. (1989); (10) Carrera et al. (2007).

Table 7. Globular clusters used in Fig. 9.

Cluster	M_V	Age (Gyr)	Notes	References
NGC 104	-9.42	12.16	9	2, 3, 8
NGC 288	-6.75	11.52	9	2, 3, 8, 9
NGC 362	-8.43	10.24	9	2, 8, 9
NGC 1261	-7.80	10.11	0	
Palomar 1	-2.52	6.66	0	
Eridanus	-5.13	9.09	0	
NGC 1851	-8.33	10.37	9	8, 10
NGC 1904	-7.86	11.39	9	3
NGC 2298	-6.31	12.93	9	
NGC 2419	-9.42	10.08	9	4, not in 1
NGC 2808	-9.39	10.62	9	2, 3
E3	-4.12	11.78	0	
Palomar 3	-5.69	10.62	7	14
NGC 3201	-7.45	10.5	9	2, 3
Palomar 4	-6.01	9.73	0	
NGC 4147	-6.17	12.29	5	
NGC 4372	-7.79	12.8	0	
Ruprecht 106	-6.35	10.11	0	
NGC 4590	-7.37	12.03	9	2, 3
NGC 4833	-8.17	12.93	0	
NGC 5024	-8.71	13.31	8	1
NGC 5053	-6.76	12.93	0	
NGC 5139	-10.26	13.00	9	
NGC 5272	-8.88	11.26	8	1
NGC 5286	-8.74	13.06	6	9
NGC 5466	-6.98	13.60	1	1
NGC 5694	-7.83	13.44	0	
IC 4499	-7.32	12.00	1	6
NGC 5824	-8.85	12.8	0	
NGC 5897	-7.23	13.18	0	
NGC 5904	-8.81	10.88	9	2, 3
NGC 5927	-7.81	11.65	9	8
NGC 5946	-7.18	11.9	0	
NGC 5986	-8.44	12.42	0	
NGC 6093	-8.23	12.93	8	2
NGC 6101	-6.94	12.42	0	
NGC 6121	-7.19	12.93	9	2, 3
NGC 6144	-6.85	13.82	0	
NGC 6139	-8.36	11.39	0	
NGC 6171	-7.12	12.67	9	3
NGC 6205	-8.55	13.06	9	1, 2
NGC 6229	-8.06	99.99	0	
NGC 6218	-7.31	12.67	9	2, 3
NGC 6235	-6.29	99.99	0	
NGC 6254	-7.48	11.78	9	2, 3
NGC 6256	-7.15	99.99	0	
NGC 6266	-9.18	11.39	0	
NGC 6273	-9.13	12.67	0	
NGC 6284	-7.96	11.65	0	
NGC 6287	-7.36	13.7	0	
NGC 6341	-8.21	14.21	8	1
NGC 6342	-6.42	11.78	0	
NGC 6352	-6.47	11.14	9	8
NGC 6366	-5.74	11.65	8	2

Notes. As in Table 6.

References. Ages and M_V from the updated version of the GC database by Harris (1996). (1) Lardo et al. (2011); (2) Monelli et al. (2013); (3) Carretta et al. (2010); (4) Beccari et al. (2013); (5) Kacharov et al. (2013); (6) Walker et al. (2011); (7) Origlia et al. (2011); (8) Pancino et al. (2010b); (9) Kayser et al. (2008); (10) Carretta et al. (2011); (11) Cohen & Melendez (2005); (12) Smith et al. (2005); (13) Ferraro et al. (2009); (14) Koch et al. (2009).

Table 7. continued.

Cluster	M_V	Age (Gyr)	Notes	References
NGC 6362	-6.95	12.03	0	
NGC 6388	-9.41	12.19	9	3, 8
NGC 6402	-9.10	11.14	0	
NGC 6397	-6.64	11.50	9	2, 3
Palomar 6	-6.79	12.67	0	
Terzan 5	-7.42	10.00	7	13
NGC 6440	-8.75	11.20	7	7
NGC 6441	-9.63	11.00	9	3
Terzan 6	-7.59	10.62	0	
Terzan 9	-3.71	11.14	0	
NGC 6528	-6.57	11.01	0	
NGC 6541	-8.52	11.01	8	2
NGC 6553	-7.77	13.44	0	
NGC 6584	-7.69	11.39	0	
NGC 6624	-7.49	11.26	0	
NGC 6637	-7.64	11.65	0	
NGC 6652	-6.66	11.65	0	
NGC 6656	-8.50	13.57	9	8, 9
NGC 6681	-7.12	12.42	0	
NGC 6712	-7.50	12.00	8	2
NGC 6717	-5.66	12.8	0	
NGC 6723	-7.83	12.93	0	
NGC 6752	-7.73	13.06	9	2, 3, 8
NGC 6779	-7.41	14.08	0	
NGC 6809	-7.57	13.06	9	2, 3, 8, 9
Palomar 11	-6.92	10.40	9	
NGC 6838	-5.61	12.03	9	3
NGC 6864	-8.57	12.00	7	5
NGC 6934	-7.45	11.26	8	2
NGC 6981	-7.04	11.14	8	2
NGC 7006	-7.67	12.00	7	12
NGC 7078	-9.19	12.93	9	1, 2, 3, 8, 9
NGC 7089	-9.03	12.29	8	1
NGC 7099	-7.45	13.82	9	2, 3
NGC 7492	-5.81	11.9	7	11

Table 8. Clusters in other galaxies used in Fig. 9.

Galaxy	Cluster	M_V	log Age	Notes	References
LMC	NGC 1466	-7.59	10.00	0	11
	NGC 1644	-5.61	9.19	1	1, 11
	NGC 1651	-7.17	9.30	3	6, 11
	NGC 1652	-5.37	9.23	1	1, 11
	NGC 1754	-7.36	10.09	0	11
	NGC 1751	-6.83	9.15	8	1, 11, 18, 20
	NGC 1783	-8.11	9.18	5	11, 18, not in 1, 6
	NGC 1786	-8.41	10.08	9	5, 11, 21
	NGC 1795	-6.08	9.11	1	1, 11
	NGC 1806	-7.50	9.18	8	1, 11, 18
	NGC 1835	-8.74	10.12	0	11
	NGC 1841	-7.80	9.99	0	11
	NGC 1844	-6.31	9.00	8	10, 11
	NGC 1846	-7.82	9.17	8	1, 11, 18, 21
	NGC 1852	-6.49	9.12	8	1, 11
	NGC 1866	-9.98	8.12	3	4, 11
	NGC 1898	-7.82	10.05	7	8, 11
	NGC 1916	-8.93	10.10	0	11
	NGC 1917	-6.17	9.11	8	1, 11
	NGC 1928	-6.83	9.23	0	11
	NGC 1939	-7.43	9.20	0	11
	NGC 1978	-7.80	9.30	2	1, 11, not in 6
	NGC 1987	-6.76	9.03	8	1, 11, 18
	NGC 2005	-9.92	10.12	7	8, 11
	NGC 2019	-9.97	10.15	7	8, 11
	NGC 2108	-6.18	9.01	8	1, 11, 18
	NGC 2154	-6.71	9.15	8	1, 11
	NGC 2155	-6.68	9.51	1	2, 11
	NGC 2173	-7.33	9.33	5	2, 11, not in 6
	NGC 2209	-7.90	8.98	8	9, 11
	NGC 2210	-8.00	10.10	7	5, 11
	NGC 2257	-7.06	10.10	7	5, 11
SMC	IC 2146	-6.09	9.19	1	1, 11
	Hodge 7	-6.24	9.17	8	1, 11
	Hodge 11	-7.50	10.08	7	8, 11
	SL 529	-4.96	9.35	8	3, 19
	SL 556	-9.29	9.34	1	2, 11
	SL 862	-4.83	9.18	8	1, 11
	NGC 121	-8.51	10.04	8	12, 13
	NGC 152	-9.49	9.15	0	17
	NGC 176	-6.24	8.30	0	17
	Lindsay 1	-7.39	9.86	1	12, 15
	Kron 3	-7.75	9.81	1	12, 15
	NGC 339	-7.42	9.78	1	12, 15
	NGC 361	-10.12	9.91	0	12, 17
	NGC 416	-8.03	9.78	1	12, 15
	Lindsay 38	-5.08	9.81	1	12, 15
	NGC 411	-7.49	9.22	8	14, 17
	NGC 419	-8.85	9.18	8	12, 15
	NGC 458	-7.74	9.78	0	17

Notes. As in Table 6.

References. (1) Milone et al. (2009); (2) Bertelli et al. (2003); (3) Piatti (2013); (4) Mucciarelli et al. (2011); (5) Mucciarelli et al. (2009); (6) Mucciarelli et al. (2008); (7) Letarte et al. (2006); (8) Johnson et al. (2006); (9) Keller et al. (2012); (10) Milone et al. (2013); (11) Baumgardt et al. (2013); (12) Glatt et al. (2009); (13) Rubele et al. (2010); (14) Girardi et al. (2013); (15) Glatt et al. (2008); (16) Mackey & Gilmore (2003a); (17) Mackey & Gilmore (2003b); (18) Goudfrooij et al. (2011); (19) Bica et al. (1996); (20) Rubele et al. (2011); (21) Rubele et al. (2013); (22) Mackey & Gilmore (2003c); (23) Pancino et al. (2010b); (24) Kayser et al. (2008).

Table 8. continued.

Galaxy	Cluster	M_V	log Age	Notes	References
Fnx	Fornax 1	-5.32	10.06	7	7, 16
	Fornax 2	-7.03	10.06	7	7, 16
	Fornax 3	-7.66	10.06	7	7, 16
	Fornax 4	-6.83	9.96	0	16
	Fornax 5	-6.82	10.06	0	16
Sgr	NGC 6715	-9.98	10.17	9	22
	Terzan 7	-5.01	9.88	3	22, 23
	Terzan 8	-5.07	10.16	0	22
	Arp 2	-5.29	10.10	0	22
	Palomar 12	-4.47	9.91	4	22, 23, not in 24